Acoustic Propagation in Turbulent Layers

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***Abstract*- The objective of this work was to determine the extent to which acoustic propagation varies in the vicinity of topographic features where the flow oscillates between laminar and turbulent states. Since these topographic features are ubiquitous in coastal areas, the results will impact ACOMMS performance in these areas. In a recent experiment by Moum and Nash, oceanographic measurements were made around a small bank off the western continental shelf (Fig. 1). Temperature, salinity, and turbulent dissipation rate measurements were obtained from this experiment and broadband (9-11kHz) acoustic simulations done to determine the impact of the turbulent sound speed field on acoustic propagation. Acoustic simulations show an overall increase in transmission loss of about 10-15dB within the 10-11KHz band. This corresponds to the times where intense turbulence occurs. The transmission loss correlates well with the turbulent dissipation rate.**

I. Introduction

Acoustic communications (ACOMMS) is of interest in a variety of geographic areas. Many areas are characterized by highly variable oceanographic conditions that can lead to ineffective ACOMMS performance. In this paper we are particularly concerned with oceanographic environments that develop turbulent bottom layers and investigating the degree to which turbulent flow affects acoustic signals and at what frequencies these effects become pronounced. The work here was motivated in part by a paper by Di Lorio and Farmer[1]. In that paper high frequency (67.6kHz) acoustic signals were transmitted in order to estimate a path-averaged turbulent dissipation rate. This paper studies the direct effects of turbulence, as measured by the turbulent dissipation rate, on acoustic signals as a function of time. We develop an idealized turbulent bottom layer from experimental oceanographic data. The measured sound speed is used to do acoustic model simulations.

II. Oceanographic experiment and data analysis

Fig. 1 shows the experimental site known as Stonewall Bank. For a complete description see Moum and Nash[2]. The inset of Fig. 1 shows Stonewall Bank rising approximately 15m above a relatively flat bottom of 60m depth. The oceanographic vessel transited around the triangle shown in the inset over a 14-hour time period stopping at stations about 100-200m apart in order to take measurements. The longer legs of the triangle were about 3km long. The time between each station was on the order of 2 hours. At each station, measurements of current, temperature, conductivity, and fine-structure measurements were made. Sound speed estimates were obtained from the temperature and conductivity measurements, while turbulent dissipation rates (e) were evaluated from the measured vertical shear $\left(\partial u/\partial z\right)$ in velocity using:

$$e = 7.5\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2}$$

where ν is the molecular viscosity of seawater.

In order to simplify the acoustic analysis, all the bathymetric variation was removed and a flat bottom was assumed at 54m. The sound speed and turbulent dissipation measurements made at the last depth above 54m were extended to that depth. All measurements taken along the longer legs of the triangle were combined into a single track. Sound speed and turbulent dissipation was then interpolated in range, depth and time. The range and depth interpolation was to 20m and 0.1m, respectively, and the time interpolation was 2min. The interpolation intervals were chosen based on the convergence of acoustic model results. Fig. 2 shows the interpolated sound speed for the time period when the turbulent dissipation rate was at a minimum. If the remaining time periods are viewed, the sound speed structure and the turbulent dissipation rate can be characterized as weakly range dependent with strong time dependence. It can also be seen in the remaining data that all the dynamic sound speed and turbulent dissipation rate behavior occurs at depths greater than about 30m. The upper part of the water column is relatively stable.

Figs. 3 and 4 show the sound speed and turbulent dissipation rate as a function of depth and time, respectively. The figures show a cut of the four-dimensional data at 2km from the southwest vertex of the triangle shown in the inset of Fig. 1.

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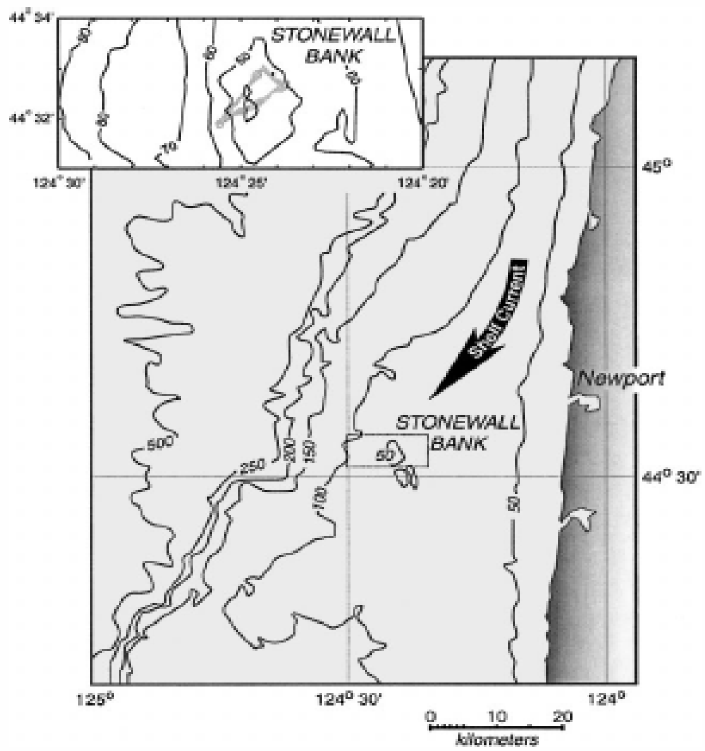

Fig. 1. Experimental site off the coast of Oregon

In the acoustic analysis, discussed in the next section, the acoustic source and receiver are both at a depth of 53m, one meter off the bottom. The two figures show the sound speed and turbulent dissipation rate at the receiver location that is 2km from the source that was simulated to be at the southwest vertex of the triangle. The source and receiver depths and source-receiver range was chosen based on a likely ACOMMS geometry. Figs. 5 and 6 display the turbulent dissipation and sound speed, respectively, at the receiver depth of 53m (green dots). In Fig. 5, the turbulent dissipation is at its highest at 4h with a value of 10^{-5} m^2s^{-3} and there is a second maximum at 10h with a value of 10^{-6} m^2s^{-3}. At 12-14h the turbulent dissipation is at a minimum of about 10^{-7} m^2s^{-3}. Fig. 6 shows that during this same time period of 4-14h, the sound speed changes are less than 1 m/s. If weak range dependence is assumed, the turbulent dissipation rate and sound speed at the receiver as a function of time is considered to be a good indicator of major oceanographic changes taking place along the acoustic track.

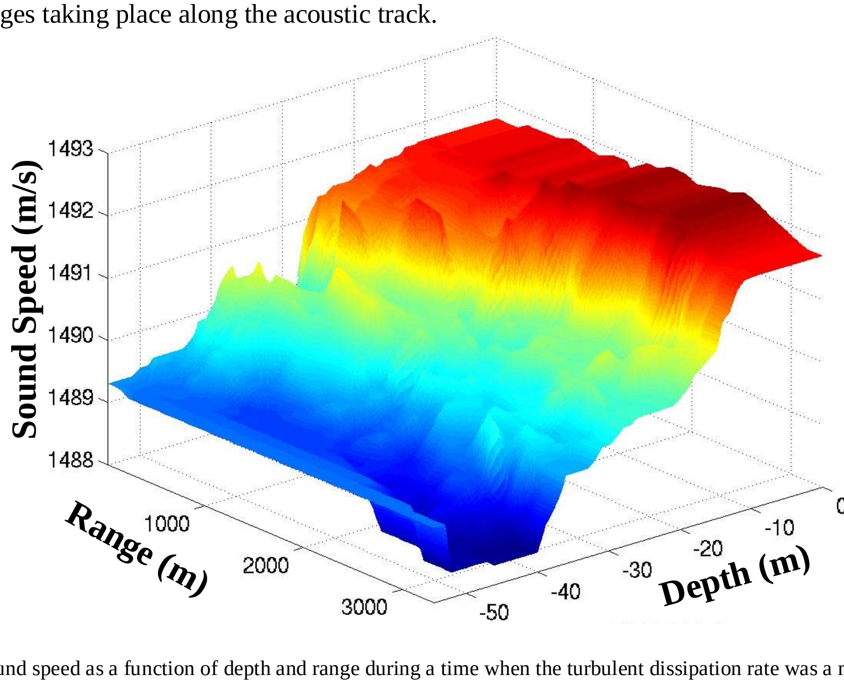

Fig. 2. Sound speed as a function of depth and range during a time when the turbulent dissipation rate was a minimum.

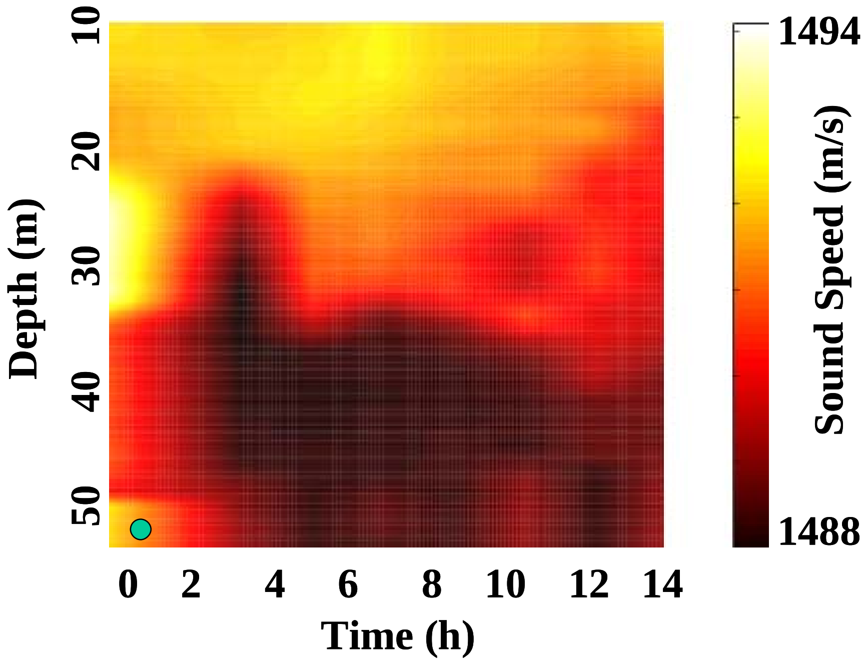

Fig. 3. Sound speed as a function of depth and time at a range of 2km.

Even though this is a highly idealized case, it is sufficient to get an idea of the degree of turbulence required in order to impact the acoustic propagation and at what frequencies these effects begin to manifest themselves. Figs. 5 and 6 also show that if this degree of turbulence, as measured by the turbulent dissipation rate, does significantly affect the acoustic propagation; the sound speed is not a very useful measure in this case.

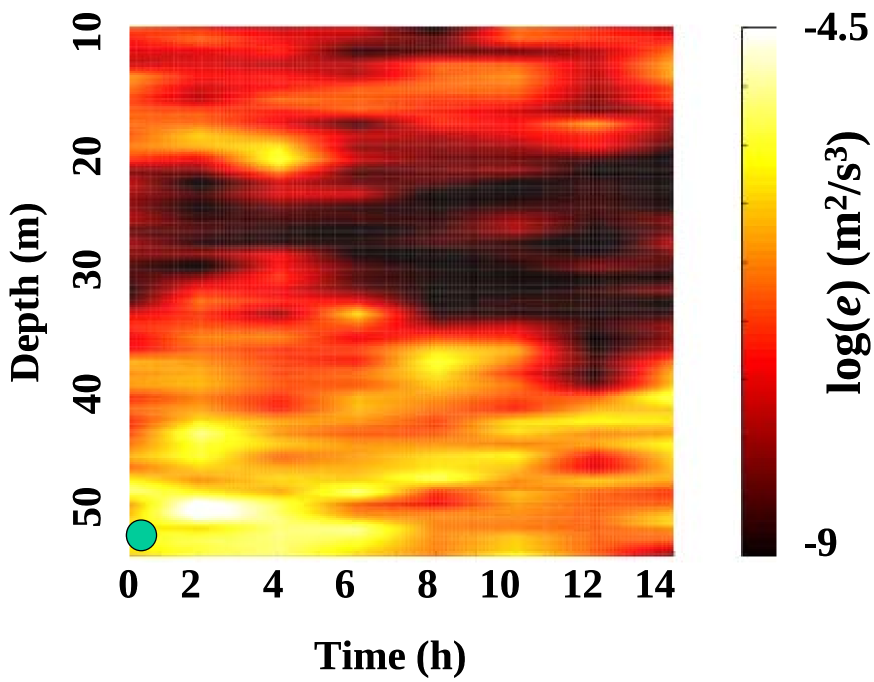

Fig. 4. Turbulent dissipation rate as a function of depth and time at a range of 2km.

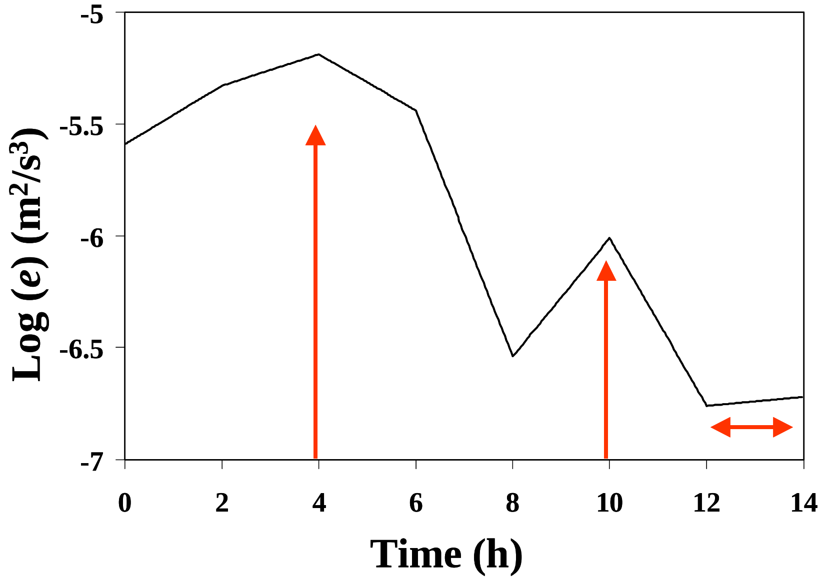

Fig. 5. Turbulent dissipation rate as a function of time at 53m and a range of 2km.

III. ACOUSTIC ANALYSIS

For the acoustic analysis, the range, depth and time dependent sound speed data was input into the Collins, FEPE model[3]. The acoustic source and receiver depths are at 53m and the source to receiver range is 2km. As shown in Fig.1 by the bold arrow indicating shelf current, the propagation is from the southwest to northeast, against the current. The bottom properties used are: sound speed = 1600m/s, density = 2.0g/cm^3, and attenuation = .1dB/wavelength. The model calculated complex pressures between 9kHz and 11kHz in 1Hz steps for eight time periods corresponding to the times labeled in Fig. 6. The time waveforms were obtained by Fourier transform. The waveforms are displayed in Fig. 7. The figure shows time in hours along the vertical and acoustic arrival time in ms along the horizontal. The waveforms were computed every 2h. Eight waveforms are displayed in Fig. 7. From Fig. 5, the lowest turbulent dissipation is from 12-14h. The 14h period will be used as a reference waveform. Overall, turbulence increases from 14h to 4h as shown in Fig. 5. The time waveforms of Fig. 7 show high amplitude first arrivals at 14h arriving at 3ms.

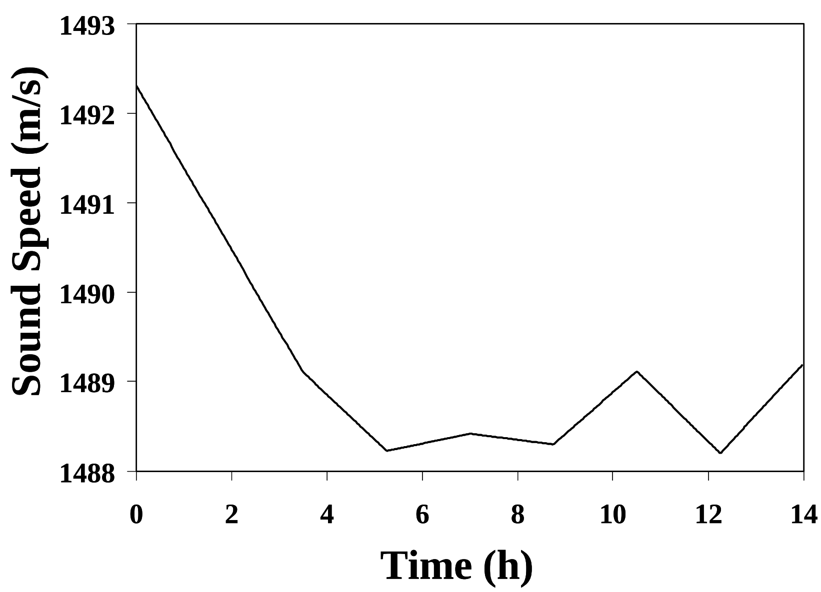

Fig. 6. Sound speed as a function of time at 53m and a range of 2km

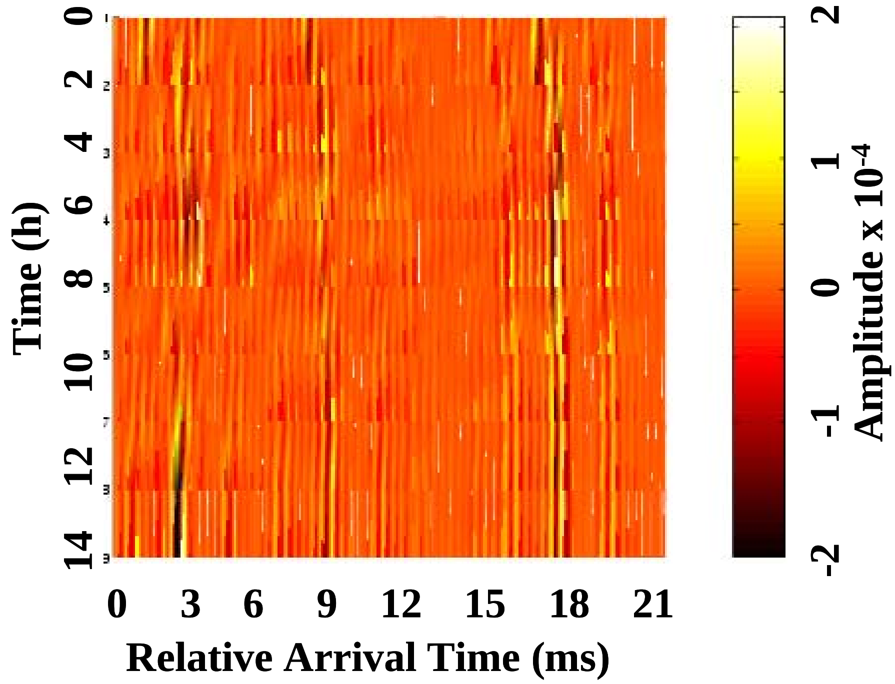

Fig. 7 Simulated time waveforms with a bandwidth of 9-11kHz.

The first arrivals here consist primarily of unresolved bottom-surface and surface-bottom paths. At a range of 2km there is no direct arrival. These lower-angle arrivals carry most of the acoustic energy during times of low turbulence. At higher angles, shown at about 9ms and 18ms in Fig. 7, the acoustic energy interacts more often with the bottom, stripping out significant energy. At the higher angles, acoustic energy is spending less time propagating through the turbulent layer. Therefore, at 18ms the waveforms display greater temporal coherence but suffer more loss due to bottom interaction.

Fig. 8 displays the power spectra of the waveforms of Fig. 7. The figure shows the effect of turbulence on frequency. For frequencies less than 10kHz, the spectra are rather uniform from 14-0h. Starting at about 10kHz, the effects of turbulence are beginning to become significant. At 10kHz and above, the signal undergoes considerable fading from 12-2h.

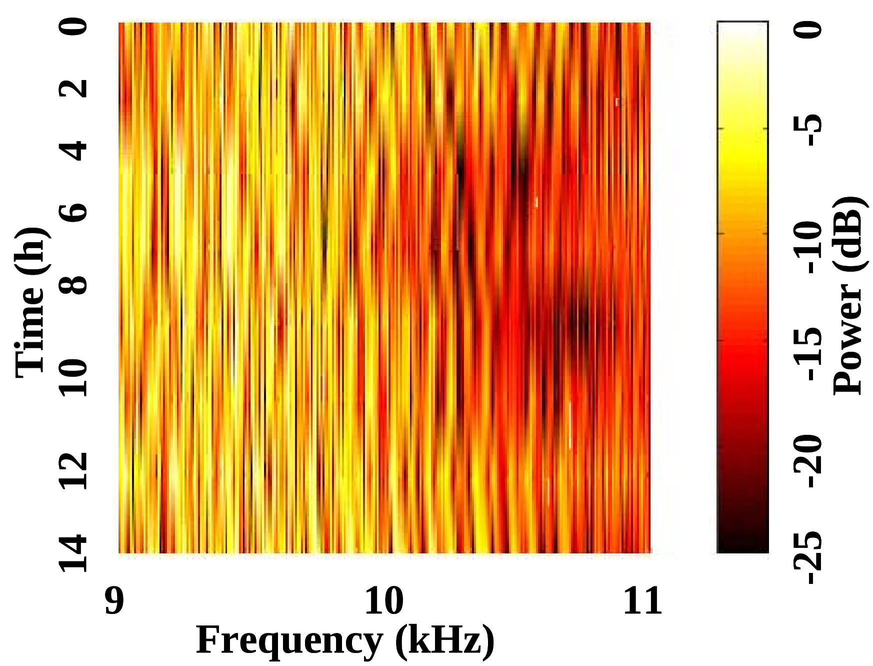

Fig. 8. Power spectra of time waveforms of Fig. 6.

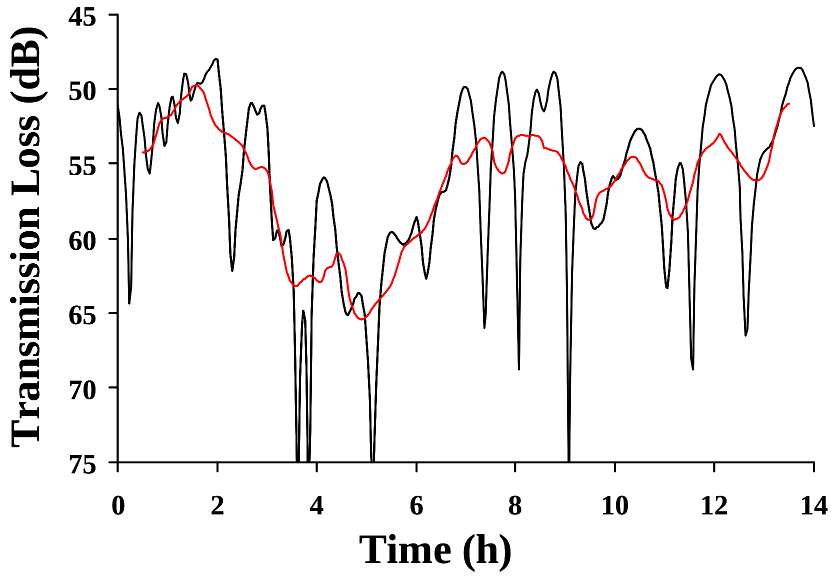

Fig. 9. Transmission loss as a function of time at 10kHz. depth=53m, range=2km.

In Fig. 9, the black curve is a plot of the raw transmission loss computed from the FEPE model at 10kHz. This is not a slice of the power spectra shown in Fig. 8. The transmission loss here is computed every 2min with range and depth dependent sound speeds. This transmission loss was then averaged over 1h time intervals and is shown by the red curve in Fig. 9. Averaging was also done in range and depth over a few wavelengths with about the same results. At the 14h reference time, the transmission loss is about 50dB. From 2-7h the signal fades, reaching a maximum of 60-65dB between 3-6h, some 10-15dB below the low turbulence state at 14h. A smaller fade can be observed between 9-11h. The time periods of 3-6h and 9-11h correlate well with the turbulent dissipation rates shown by the up-arrows in Fig. 5. No such correlation is observed in the sound speed shown in Fig. 6.

IV. Conclusions

This study was undertaken in order to determine if turbulent bottom boundary layers are an issue for ACOMMS performance. If so, what frequency regimes are likely to be affected and to what degree for a chosen measure of turbulence. Even though the results presented here are from an ideal case crafted from oceanographic measurements, we conclude that turbulent bottom boundary layers are probably an ACOMMS performance issue for frequencies down to 10kHz. These layers become more of an issue with increasing frequency. It was shown that at 10kHz, signal fading as much as 10-15 dB over a period of hours could be observed when the turbulent dissipation rate around the receiver is on the order of 10^{-5} and 10^{-6} m^2s^{-3}. For higher frequencies, much lower turbulent dissipation rates could be tolerated.

These results will help in the planning of a 2008 experiment in the Pinnacles area of the Gulf of Mexico where it is intended to do an ACOMMS experiment in the 9-15kHz regime. One of the objectives here is to determine if ACOMMS performance can be directly predicted from oceanographic measurements made at the transceiver. Acoustic propagation measurements are planned in the Pinnacles area during times of both laminar and turbulent flow. Acoustic signals will be received on multiple vertical arrays from near-bottom sources. Before, during and after the acoustic transmissions, oceanographic measurements will be used to characterize the flow in the vicinity of a selected topographic feature. This will allow the acoustic energy to be correlated with critical flow variables such as the Froude, Richardson, Reynolds numbers, and turbulent dissipation rate. The critical ocean variables will be correlated with the acoustic energy as a function of time and space. Of particular interest is the Richardson number, Ri. As discussed by Di lorio and Farmer[1] (eqn. 2), Ri is the ratio of the potential energy of stratification to the kinetic energy of the flow. For large Ri (>1), the stratification should be stable. For small Ri (<1), kinetic energy of the flow dominates implying strong turbulence. During stable stratification (Ri>1) we should expect stable multipath and the ping-to-ping correlation should be high. As Ri decreases, the ping-to-ping correlation should degrade due to turbulent scattering.

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